

The environmental LCA of steel vs HDPE car fuel tanks with varied pollution control

Ndumiso G. Dlamini · Kenta Fujimura · Eiji Yamasue ·
Hideyuki Okumura · Keiichi N. Ishihara

Received: 3 March 2010 / Accepted: 8 March 2011 / Published online: 30 March 2011
© Springer-Verlag 2011

Abstract

Purpose There has been an increasing use of plastic motor car fuel tanks in recent decades with the expected benefits of lighter weight, shape flexibility and lower cost. In this paper, the environmental life cycle assessments of mild steel and high-density polyethylene (HDPE) car fuel tanks in Japan are compared for two cases, namely the current average processes (base case), and for the same processes with the maximum currently feasible pollution control technology installed.

Materials and methods Primarily, data from Japan are used for a life cycle inventory analysis, followed by an impact assessment based on the Life Cycle Impact Assessment Method Based on Endpoint Modelling and five other indicators.

Results and discussion Mild steel shows a notably higher inventory for resources iron, manganese, zinc, coking coal, combustion coal, dolomite, limestone; for the air pollutants nitrogen oxides (NO_x) from mobile sources, PM₁₀, sulphur dioxide, hydrocarbons; and for solid waste (slag). HDPE has a higher inventory for resources liquefied natural gas reserves, oil reserves, for the air pollutants carbon dioxide, NO_x from non-mobile sources and sulphur oxides. The base case environmental impact assessment results for six indicators show HDPE and steel to have similar impacts for all but one of the indicators. With pollution control, the feasible reductions in respective pollutant inventories range

from 0% to 97%, while the corresponding impact assessment shows indicator values reduced by 0% to 29%, with slightly improved performance of mild steel relative to HDPE.

Conclusions Accounting for a 62-year period of use and recycling for the mild steel would show a further decrease in the impact of the mild steel relative to HDPE.

Keywords Fuel tanks · Impact assessment · Indicators · Life cycle inventory · Materials · Pollution control

1 Introduction

While steel automotive fuel tanks have been in use for most of the history of the motor car, the use of plastic fuel tanks is a more recent phenomenon. Although plastic fuel tanks date back to the 1950s, they only achieved major prominence in the 1970s after use by car maker Volkswagen, and it was not until the late 1980s and early 1990s that they were adopted widely in the USA (Keoleian et al. 1998). Weight benefits, the ease of shape forming and low cost are the main benefits that have been sought from the use of high-density polyethylene HDPE car fuel tanks (Bellmann and Khare 1999). Current concern about the environmental impact of industrial processes has led to the comparison of alternative materials and processes, such as mild steel and HDPE as used for car fuel tanks.

A number of authors have reported on the comparative life cycle assessment between mild steel and HDPE. Six of the eight papers reviews (Hendrickson et al. 2006; Joshi 1999; Lave et al. 1998; Stephens et al. 1998; Keoleian et al. 1997; Keoleian et al. 1998) are written by an interrelated group of researchers, associated with General Motors and SAE, the Society for Advancing Mobility Land Sea Air and Space International, and therefore some of the basic assumptions,

Electronic supplementary material The online version of this article (doi:10.1007/s11367-011-0277-7) contains supplementary material, which is available to authorized users.

N. G. Dlamini (✉) · K. Fujimura · E. Yamasue · H. Okumura ·
K. N. Ishihara

Graduate School of Energy Science, Kyoto University,
Yoshida-honmachi, Sakyo-ku,
Kyoto 606-8501, Japan
e-mail: ndumiso.dlamini@gmail.com

approach and data are, as expected, similar across this group. These papers assume that a steel fuel tank is heavier than an HDPE fuel tank of equivalent functionality, and they report that HDPE has a lower environmental impact than mild steel. However, a number of the inventory values considered are reported to be lower for steel, and such is the case for life cycle solid waste generation in the two papers by Keoleian et al. (1997 and 1998). One of the other two papers, Tung and Wang (2002) also obtains the result that HDPE has a lower impact using original factors in that impact assessment. The Yamato and Mituhara (1997) paper uses factory production data. Its finding is that HDPE has a worse impact in terms of carbon monoxide, nitrogen oxide, sulphur oxide (SO) and particulate matter 10 microns or less in size (PM₁₀). Two approaches to Life Cycle Assessment (LCA) are used in the abovementioned papers: Society of Environmental Toxicology and Chemistry (SETAC) and Economic Input–Output. The SETAC approach to LCA involves a separate cradle to grave analysis for each process, accounting for the various inputs and outputs to the whole process. The Economic Input–Output techniques, on the other hand, use data from surveys which have been conducted by classifying economic activity into sectors (481 sectors for the USA exist on the Simapro software (Product Ecology Consultants 2010) to evaluate the environmental inputs and outputs per monetary unit. This information is then used to do a life cycle assessment of a process or product, provided the monetary value and process sector are known. The SETAC approach is used to derive results in this study.

The life cycle impacts of steel vs HDPE as used for a motor car fuel tank in Japan are compared in this study. The impacts are considered, firstly through an inventory analysis, and then by doing a life cycle impact assessment using six different integrated indicator methods, including the Life Cycle Impact Assessment Method based on Endpoint Modelling (LIME) developed in Japan (Itsuno and Inaba 2003), and others. This article adds to previous studies on the topic by further considering the life cycle impacts of these materials when we apply the pollution abatement technology currently available, for example PM₁₀ (particulate matter) and nitrogen oxides (NO_x) reduction systems.

2 Methodology

2.1 Life cycle parameters

Figure 1 is an outline of the processes and energy requirements involved in the life cycle of the car fuel tanks analysed here. The stages shown are the same as those outlined in Table 1. The main assumptions are also shown in Table 1. Transport impact is included within the various stages (Tables 2 and 3).

The following analysis is conducted: the environmental burden of two 80-l car fuel tanks made of steel and HDPE, respectively in Japan are compared firstly using an inventory of inputs and outputs for the processes shown in Fig. 1. Total inventory values per substance, as well as separate inventories for production, use and disposal are presented. Determination of the comprehensive inventory is followed by an analysis of the technical severity of the burden of the inventory items (see Table 4). The full inventory and analysis are then related to an impact assessment based on LIME indicator versions 1 to 3 (Itsuno and Inaba 2003) which were developed in Japan, and other indicators for comparison. These include the Dutch Eco-Indicator 95 (Product Ecology Consultants 2009; Hunkeler et al. 1998), the Swiss Ecopoint indicator (Hunkeler et al. 1998) and the Swedish Environmental Priority Strategies for Product Design (EPS) (Bengtsson and Steen 2000; Hunkeler et al. 1998). A further analysis of the inventory is conducted, considering the current technically feasible potential reduction in certain pollutants by up to 97% depending on the respective pollutant (see Table 4), and comparing the impacts of mild steel and HDPE when this pollution control is applied.

In the use phase, a heavier fuel tank leads to decreased fuel efficiency, assuming all other factors remain equal. According to the report “On The Road in 2035” (MIT 2008), the gasoline requirement changes by 0.69 l/100 km/100 kg of car weight. Further, as the weight of the fuel tank increases, there is also an increase in the upstream energy and emissions associated with the additional gasoline. Transportation of the fuel tank equivalent weight by light van [available per ton-km on the Japan Environmental Management Association for Industry (JEMAI) database] is used as an equivalent process to model the environmental burden of carrying the fuel tank during use. The average lifespan of a car in Japan—10 years, is sourced from Hayashi et al. (2001). The average annual kilometres travelled by a private passenger vehicle in Japan (9,738 km) are sourced from EDMC (2008), using data on kilometres travelled and vehicle stocks. A further consideration is that some gasoline is quickly absorbed into the HDPE material (Mouzakis and Karger-Kocsis 1998), increasing the weight of the fuel tank for the duration of its operational lifetime. Data reflecting a 0.51 kg weight increase was included in the analysis (Nippon Steel 2009) and is shown in Table 1.

For the end-of-life treatment, HDPE was assumed to be incinerated, the most likely treatment in Japan, while steel was considered to be disposed of without recycling, except in the discussion where recycling scenario effects are considered.

2.2 Data sources

The source of data for the analysis is the JEMAI LCA database software (JEMAI 2008), which contains life cycle

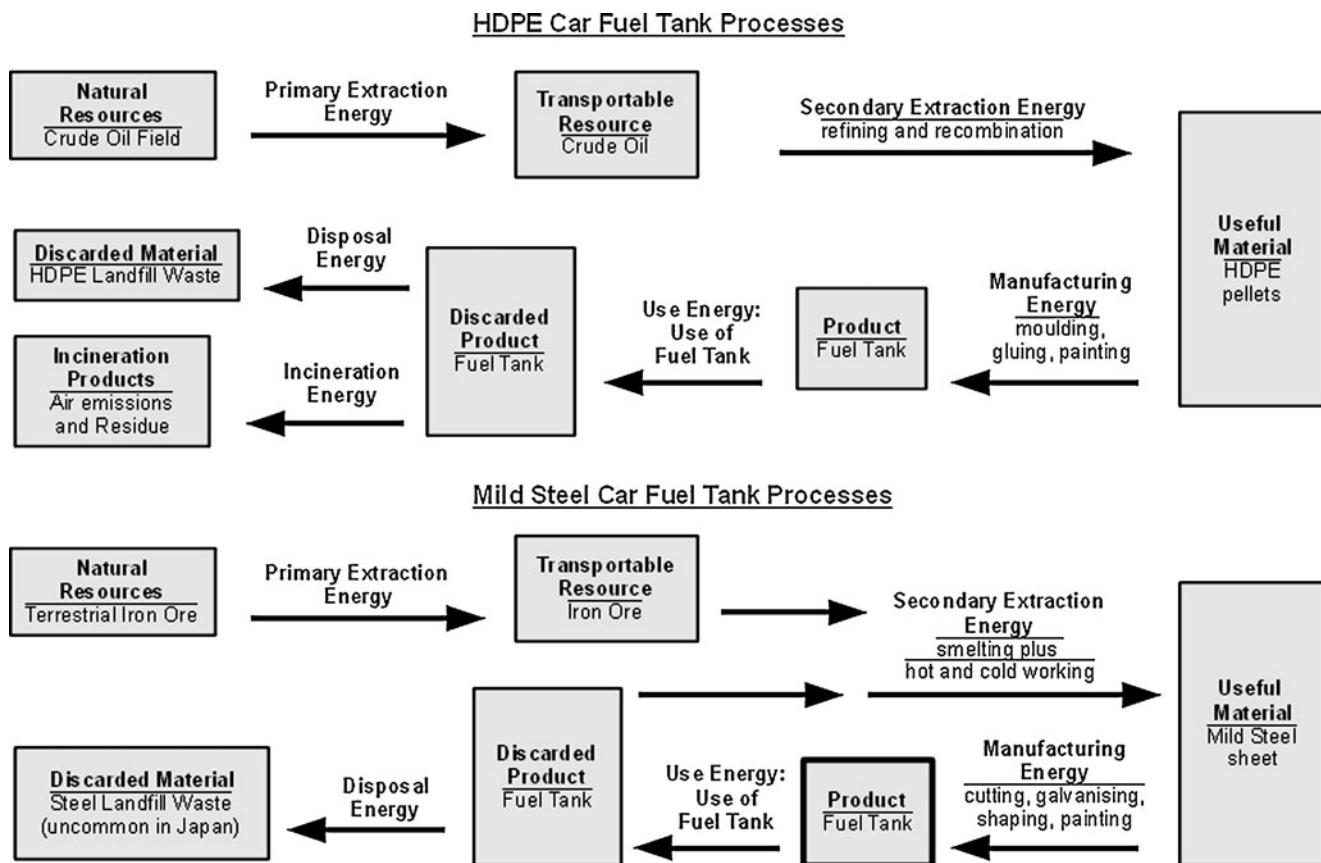


Fig. 1 Fuel tank life cycle processes and energy requirements

inventory (LCI) data for various materials and processes, primarily centered on values derived for processes in Japan. The weight of material required for the fuel tanks, as well as other finishing data, is obtained through Nippon Steel (2009). The mild steel tank analysed has a general wall thickness of 0.8 mm, while the HDPE tank has a multi-layer wall (Joshi 1999). Values for final manufacturing, shown in Table 1, are for finishing operations in Japan (Nippon Steel 2009). Their environmental impacts are small relative to the life cycle total. The main basic manufacturing and disposal data for the assessment are shown in Table 2. Data from the LCA database of the EU, known as the European Reference Life Cycle Database (ELCD 2007) is used for comparison in the table. The inventory determination (Table 3) and the calculation of the impact assessment in terms of the six mentioned indicators were carried out on the JEMAI database software.

2.3 Data quality

The basic data on fuel tank input materials and resources are considered accurate to within 0.1%, while the annual distance travelled by the car is considered accurate to within 1 km (about 0.01%). It is noteworthy that the steel

production energy figures are fairly similar for ELCD and JEMAI, and the energy required to produce 100% virgin steel in Japan is almost 10% less than the energy required in the EU. The HDPE production figures for ELCD and JEMAI are similar, at 76.7 MJ/kg and 74.8 MJ/kg, respectively (the latter is obtained by adding the required process fuels energy of 17 MJ/kg (Keoleian et al. 2000) to the 57.8 MJ/kg feedstock energy derived from the JEMAI database). The value of 103 MJ/kg for fully processed HDPE material from CBPR (2009) as shown in the table, appears too high. We assume that for extraction and manufacturing, HDPE is 100% virgin, mild steel is 98% virgin, as this inventory is readily available in the JEMAI database, compared to the 90% virgin as produced according to Nippon Steel (2009).

2.4 Data limitations

The data used rely heavily on the inventory contained in the JEMAI database (JEMAI 2008). The JEMAI inventories for mining and smelting processes are not separable for the chosen process of making steel, making it very difficult to consider the recycling of mild steel, even though the process is common.

Table 1 Assumptions for life cycle assessment

Stage in life cycle	Mild steel tank (0.8 mm)	HDPE tank
All	80 l fuel tank; 14.8 kg total weight	80 l fuel tank; 14.2 kg total weight at manufacture, 14.71 kg during use (fuel absorption—see “use” below)
Material extraction and basic production	Standard extraction, hot and cold rolling of mild steel sheet JEMAI data used	Standard extraction of crude oil, followed by chemical processes to make HDPE granules JEMAI data used
Manufacturing	About 90% virgin and 10% recycled steel used (Nippon Steel 2009) 13.05 kg steel weight in product, 1.75 kg paint in product 24% overall scrap rate from sheet/coil to finished fuel tank (Nippon Steel 2009), therefore 17.17 kg steel required for manufacture. Zinc galvanizing assumed 6.95 kWh of electricity consumed	HDPE sourced from crude oil 12.73 kg HDPE weight in product, 0.49 kg EVOH, 0.98 kg resin adhesive 1.7% overall scrap rate (Keoleian et al. 1998), therefore 12.95 kg HDPE required for manufacture 13.75 kWh of electricity consumed Energy and CO ₂ values for finishing taken from finishing operations (Nippon Steel 2009)
Use	Energy and CO ₂ values for finishing obtained from finishing operations (Nippon Steel 2009) Gasoline-driven car, driven a total of 10 years (97,381 km) Energy required for car to carry mass of steel in tank considered Use “On The Road in 2035” by MIT (2008) for weight effect on car fuel efficiency Effect of insulating properties of material on temperature of fuel ignored	Gasoline driven car, driven a total of 10 years (97,381 km) Energy required for car to carry mass of HDPE in tank considered. Use “On The Road in 2035” by MIT (2008) for weight effect on car fuel efficiency Weight increase (0.51 kg) due to gasoline absorption by material included (Nippon Steel 2009). Effect of insulating properties of material on temperature of fuel ignored Waste HDPE is incinerated
Disposal and recycling	Discarded fuel tank transported 500 km by 2-t truck to steel smelter (included in analysis) but assumption in the main analysis here is no recycling Each unit of steel is used for an average of 62 years before it disperses (Matsuno et al. 2007)—not considered in the main assessment	In the case of incineration, plastic waste incineration value used in the JEMAI inventory data

HDPE high-density polyethylene, JEMAI Japan Environmental Management Association for Industry, EVOH ethylene vinyl alcohol

3 Inventories

Table 3 shows inventories for the life cycles of the two materials in kilograms. It can be seen that relative to HDPE, mild steel shows notably higher inventory values for the resources iron, manganese, zinc, coking coal, combustion coal, dolomite, limestone, plus a number of relatively non-toxic resources and for the air pollutants NO_x from mobile sources, PM₁₀, and sulphur dioxide (SO₂) and hydrocarbons. The mild steel also shows a higher value for slag (landfill). HDPE, on the other hand has notably higher inventory values than mild steel for the resources liquefied natural gas (LNG) reserves, oil reserves; for the air pollutants carbon dioxide (CO₂), NO_x from non-mobile sources and sulphur oxides (SO_x). For both materials, the

production phase inventory is highest for most items but the use phase is notably more dominant for the substances oil reserves, CO₂, NO_x from mobile sources, PM₁₀ from mobile sources, and SO_x (see also Electronic Supplementary Material, Tables S1a, S1b, S2a and S2b).

4 Inventory analysis

Considering in particular Table 3, although there are many types of emissions to the environment from the production of car fuel tanks, the impact of these emissions are not necessarily equal. Before considering the impact assessment results below, we analyse the inventory results. Some emissions are easy to abate, being reduced to harmless

Table 2 Basic data and estimates from various sources

Name of value	Value	Source
Energy to produce 1 kg of 80% recycled steel coil (MJ)	13	ELCD LCA data (ELCD 2007)
CO ₂ emissions from production of 1 kg of 80% recycled steel coil (kg-CO ₂)	0.90	ELCD LCA data
Energy to produce 1 kg of 100% virgin steel coil (MJ)	32	ELCD LCA data and other sources for assumptions (Tufts 2008) (University of Massachusetts 2008)
Energy to produce 1 kg of virgin cold rolled steel sheet and strip (MJ)	28.2 ^a	JEMAI-LCA Pro (JEMAI 2008)
CO ₂ emissions from production 1 kg of virgin cold rolled steel sheet and strip (kg-CO ₂)	2.47 ^a	JEMAI-LCA Pro
Energy required to produce 1 kg of HDPE resin from natural resources (MJ)	76.7	ELCD LCA data
CO ₂ emissions from production of 1 kg of HDPE resin from natural resources (kg-CO ₂)	1.57 ^a	ELCD LCA and JEMAI-LCA Pro
Energy required to produce 1 kg of HDPE resin from natural resources (MJ)	74.8 ^a	JEMAI-LCA Pro
“Embodied energy coefficient” for HDPE (MJ/kg)	103	CBPR (2009)
Landfilling energy required for 1 kg of domestic waste, value applied to HDPE (MJ)	0.66	ELCD LCA data
Landfilling CO ₂ emissions for 1 kg of domestic waste, value applied to HDPE (kg-CO ₂)	0.26	ELCD LCA data
Energy from the incineration of 1 kg of HDPE (MJ)	46.3	ELCD LCA data
Useful energy from the incineration of 1 kg of HDPE (MJ)	23.1	ELCD LCA data
CO ₂ emissions from the incineration of 1 kg of HDPE (kg-CO ₂)	3.18	ELCD LCA data

HDPE high-density polyethylene, JEMAI Japan Environmental Management Association for Industry, ELCD European Reference Life Cycle Database, LCA life cycle assessment

^a Value relevant to calculations in this report

residues, or used as inputs to other industrial processes, while others are more difficult to reduce. Table 4 shows the currently available means for the abatement of a number of pollutants associated with car fuel tanks made of either mild steel or HDPE.

The analysis in Table 4 shows firstly that the nature of the impacts is not the same (column 2)—some impacts are global while some are local, and some more long term, while some are transitory. Secondly, the abatement of the impacts is not equally difficult, for example NO_x, SO_x, CO, acid gases and HC (hydrocarbons), are reduced significantly by currently available equipment for reducing air pollutants, such as the de-nox plant for NO_x (Forzatti 2001) and spray scrubbers for SO₂ (Brogren and Karlsson 1998). PM₁₀ and other particulate matter are reduced using various types of equipment at factories, such as bag filters and “cyclones” (Holt et al. 1999). Solid wastes such as slag from the steel-making process are used in a number of ways, including making them inputs for the steel-making process and for road building. In addition, cars are now commonly fitted with catalytic converters which control air pollutants, namely NO_x, CO and HC from car engine exhausts (Kaspar et al. 2003). In considering the reduction in environmental burden from the use of such systems (Table 5), it would be prudent to conduct an LCA of the

equipment and relevant processes, although the ability to reduce these pollutants is an established phenomenon. Some of the burdens and emissions are clearly more difficult to abate. These include the energy requirement, CO₂ emissions, other greenhouse gas emissions such as CH₄ and N₂O, and some solid waste emissions. These generally cannot be abated over a short period of time, and require mid- to long-term planning, behavioural change and technology.

Given the inventory results in Table 3, it is difficult to predict the indicator-based assessment result where no pollution control is applied, particularly because both HDPE and steel show high inventories for oil reserve consumption and CO₂ emissions. The impact reduction/abatement options listed in Table 4 are not considered in the indicators chosen for the initial impact assessment in Table 5 “current average case”, but are included in the second one in the same table, “with maximum pollution control”. The high reductions potential (70–97%) of the various local pollutants shown in the last column of Table 4, for which steel produces relatively more emissions, suggests that an impact assessment considering pollution reduction potentials would yield a result which improves the relative performance of mild steel as compared to HDPE.

Table 3 Life cycle inventories for mild steel and HDPE fuel tanks

Units in kg	Mild steel				HDPE			
	Total	Production	Usage	Disposal	Total	Production	Usage	Disposal
Resources								
Al reserves					1.7×10^{-5}	1.4×10^{-5}		3.1×10^{-6}
Cu reserves					3.6×10^{-6}	2.9×10^{-6}		6.3×10^{-7}
LNG reserves					0.45	0.45		
Cr reserves	9.2×10^{-3}	9.2×10^{-3}						
Fe reserves	17.2	17.2						
Mn reserves	0.12	0.12						
Ni reserves	4.5×10^{-4}	4.5×10^{-4}						
Pb reserves	0.033	0.033			1.3×10^{-7}	1.1×10^{-7}		2.3×10^{-8}
U reserves	1.5×10^{-4}	1.5×10^{-4}	2.4×10^{-6}	7.4×10^{-9}	1.3×10^{-4}	1.3×10^{-4}	2.4×10^{-6}	-6.5×10^{-8}
Zn reserves	0.28	0.28			7.3×10^{-7}	6.0×10^{-7}		1.3×10^{-7}
Coal (coke)	12	12			5.0×10^{-6}	4.1×10^{-6}		8.9×10^{-7}
Coal (combustion)	5.5	5.5	0.027	8.4×10^{-5}	1.5	1.5	0.027	-7.4×10^{-4}
Dolomite	0.39	0.39						
Fluorspar	0.036	0.036						
Limestone	4.8	4.8			0.15	2.1×10^{-5}		0.15
Natural gas	0.97	0.96	0.012	3.9×10^{-5}	0.70	0.68	0.013	-3.5×10^{-4}
Oil reserves	142	1.16	141	0.434	155	14.6	140	0.016
Silica sand	2.8×10^{-3}	2.8×10^{-3}			1.1×10^{-6}	8.7×10^{-7}		1.9×10^{-7}
Air emissions								
CO ₂	499	46.6	451	1.39	506	24.3	448	34.4
As	1.4×10^{-7}	1.4×10^{-7}	2.3×10^{-9}	7.1×10^{-12}	1.3×10^{-7}	1.2×10^{-7}	2.3×10^{-9}	-6.2×10^{-11}
CH ₄	4.3×10^{-4}	4.3×10^{-4}	2.7×10^{-6}	8.3×10^{-9}	2.9×10^{-4}	2.9×10^{-4}	2.7×10^{-6}	1.5×10^{-6}
Cd	1.2×10^{-8}	1.1×10^{-8}	1.9×10^{-10}	5.8×10^{-13}	1.0×10^{-8}	1.0×10^{-8}	1.9×10^{-10}	-5.1×10^{-12}
Cr	2.6×10^{-7}	2.5×10^{-7}	4.2×10^{-9}	1.3×10^{-11}	2.3×10^{-7}	2.2×10^{-7}	4.1×10^{-9}	-1.1×10^{-10}
Hg	1.7×10^{-7}	1.7×10^{-7}	2.8×10^{-9}	8.5×10^{-12}	1.5×10^{-7}	1.5×10^{-7}	2.7×10^{-9}	-7.5×10^{-11}
N ₂ O	7.9×10^{-3}	6.4×10^{-4}	7.3×10^{-3}	2.2×10^{-5}	9.8×10^{-3}	3.8×10^{-4}	7.2×10^{-3}	2.2×10^{-3}
NMHC	3.1×10^{-4}	3.0×10^{-4}	5.0×10^{-6}	1.6×10^{-8}	2.8×10^{-4}	2.7×10^{-4}	5.0×10^{-6}	-1.4×10^{-7}
NO _x	0.026	0.015	1.1×10^{-2}	3.5×10^{-5}	0.064	0.037	0.011	0.016
NO _x (mobile source)	0.69	0.022	0.66	5.3×10^{-3}	0.66×10^{-1}	8.7×10^{-4}	0.66×10^{-1}	4.1×10^{-6}
Ni	2.9×10^{-7}	2.8×10^{-7}	4.7×10^{-9}	1.4×10^{-11}	2.6×10^{-7}	2.5×10^{-7}	4.7×10^{-9}	-1.3×10^{-10}
PM ₁₀ (mobile source)	0.032	1.6×10^{-3}	0.030	7.7×10^{-5}	0.030×10^{-2}	6.4×10^{-5}	0.030×10^{-2}	3.0×10^{-7}
Pb	6.7×10^{-7}	6.6×10^{-7}	1.1×10^{-8}	3.4×10^{-11}	6.0×10^{-7}	5.9×10^{-7}	1.1×10^{-8}	-3.0×10^{-10}
SO ₂	0.018	0.013	5.3×10^{-3}	1.6×10^{-5}	6.6×10^{-3}	1.3×10^{-3}	5.3×10^{-3}	1.5×10^{-5}
SO _x	0.098	5.4×10^{-3}	0.092	2.9×10^{-4}	0.14	0.037	0.092	6.9×10^{-3}
Dust	3.2×10^{-3}	2.4×10^{-3}	7.8×10^{-4}	2.4×10^{-6}	2.3×10^{-3}	2.1×10^{-4}	7.7×10^{-4}	1.4×10^{-3}
Hydrocarbons	0.036	2.8×10^{-3}	0.033	3.4×10^{-4}	0.033	1.7×10^{-4}	0.033	6.0×10^{-7}
Water								
As					1.7×10^{-10}	1.4×10^{-10}		3.0×10^{-11}
BOD					1.9×10^{-9}	1.9×10^{-9}		
Cd					2.6×10^{-11}	2.1×10^{-11}		4.6×10^{-12}
Cr					5.1×10^{-10}	4.2×10^{-10}		9.1×10^{-11}
Hg					1.7×10^{-11}	1.4×10^{-11}		3.0×10^{-12}
Industrial								
Industrial waste landfill (unspecified)					2.0	1.8×10^{-7}		2.0
Low level radioactive waste	1.0×10^{-4}	1.0×10^{-4}	1.7×10^{-6}	$5.2 \cdot 9$	9.2×10^{-5}	9.1×10^{-5}	1.7×10^{-6}	-4.6×10^{-8}
Plastic wastes					2.7×10^{-9}	2.2×10^{-9}		4.8×10^{-10}

Table 3 (continued)

Units in kg	Mild steel				HDPE			
Item	Total	Production	Usage	Disposal	Total	Production	Usage	Disposal
Rubbles (landfill)					5.3×10^{-9}	4.4×10^{-9}		9.5×10^{-10}
Slag (landfill)	6.4×10^{-1}	6.4×10^{-1}			6.9×10^{-6}	5.7×10^{-6}		1.2×10^{-6}

Al aluminum, *Cu* copper, *LNG* liquefied natural gas, *Cr* chromium, *Fe* iron, *Mn* manganese, *Ni* nickel, *Pb* lead, *U* uranium, *Zn* zinc, CO_2 carbon dioxide, *As* arsenic, CH_4 methane, *Cd* cadmium, *Hg* mercury, N_2O nitrous oxide, NO_x nitrogen oxides, *Ni* nickel, SO_2 sulphur dioxide, SO_x sulphur oxides, *HDPE* high-density polyethylene, *BOD* biochemical oxygen demand

5 Impact assessment

Part of Table 5 shows the impact assessment “current average case”, of the mild steel and HDPE fuel tanks, using a number of indicators. The results show that the steel and HDPE tanks have similar environmental impacts according to all the impact assessment indicators except one, the EPS method—according to which steel has a 25% higher

impact. In Table 5, for the final three columns “with maximum pollution control”, NO_x , PM_{10} and slag are reduced according to the potential percentage reductions mentioned in Table 4. In the maximum pollution control scenario, steel improves relative to HDPE, so that it has a lower impact on all indicators except EPS. While the EPS indicator maintains the same impact values for the two materials before and after pollution reduction, the reduction

Table 4 Environmental burdens from car fuel tank manufacture and abatement options

Impact	Nature of impact	Main life cycle stages where featured	Options for impact reduction
Energy requirement	Generally infrastructure, natural resource and space requirements	All	Increased efficiency (mid to long term only)
CO ₂ emissions	Global warming effect	Production Use Disposal	No practical direct means
Other greenhouse gases (e.g. CH ₄ , N ₂ O)	Global warming effect	Production Use Disposal	Limited or no practical direct means
NO _x , SO _x , CO, HC, acid gases	Brown haze (smog) Health effects	Production Use	Catalytic converters Gas removal systems such as de-nox plants, scrubbers (NO _x reduction potential is at least 70%) (Burtraw et al. 2001). For mobile sources, NO _x reduction potential is 80% (Ehsan and Al Nur 2003)
Particulate matter (PM ₁₀)	Lung disease Visibility reduction	Production Use	Particulate filtration systems e.g. filter bags, cyclone dust capturing systems (the PM ₁₀ reduction potential is 93% (Aarnink et al. 2007). For mobile sources, PM ₁₀ reduction potential is 90% (Ehsan and Al Nur 2003))
Solid waste	Slag from steelmaking Scrap and metal turnings from tank production process Waste plastic	Production Disposal Scrap is recycled	Slag from steelmaking is re-used in steelmaking and as construction filling (97% reduction is achievable (Motz and Geisele 2001)) Metal turnings can be filtered from waste water
Resource depletion	Depletion of iron ore resource (steel tank) Depletion of crude oil resource	Production (material extraction) Use (in the case of crude oil) Disposal	Iron depletion can be slowed through recycling and processing efficiency improvements (iron resource depletion can be slowed by to a factor of 5 at 80% recycling rate compared to a situation of no recycling (Norgate and Rankin 2002)) HDPE recycling not yet practical

CO_2 carbon dioxide, CH_4 methane, N_2O nitrous oxide, NO_x nitrogen oxides, SO_x sulphur oxides, *CO* carbon monoxide, *HC* hydrocarbon, *HDPE* high-density polyethylene

Table 5 Car fuel tank life cycle impact assessments using a number of indicators

Indicator	Units	Current average case			With maximum pollution control		
		Mild steel value	HDPE value	Ratio mild steel/HDPE	Mild steel value	HDPE value	Ratio mild steel/HDPE
LIME Ver. 1	Yen	1,800	1,790	1.01	1,340	1,350	0.993
LIME Ver. 2	Points	1,190	1,190	1	889	898	0.990
LIME Ver. 3	Points	1,340	1,340	1	954	970	0.984
Eco 95 method	Points	3.48	3.59	0.969	2.54	2.65	0.958
Ecopoints method	Points	158,000	162,000	0.975	117,000	120,000	0.975
EPS method	Points	137	110	1.25	137	110	1.25

HDPE high-density polyethylene, EPS Environmental Priority Strategies for Product Design

for the remaining five indicators ranges from 25% to 29% depending on the indicator and material.

6 Analysis of inventory and impact assessment results

The results in Table 5 show a consistency with the technical analysis of the inventory (see Table 3) considering local/global nature of impacts, and also considering abatement options (see Table 4). The indicator-based impacts for the HDPE and mild steel tanks are similar for the base case. These indicator values decrease by 0% to 29% with the application of pollution control, while the mild steel impact decreases by a larger value relative to the HDPE value. The EPS method is the only one among the indicators which shows mild steel to have a higher impact than HDPE after the application of pollution control. The EPS indicator described by Bengtsson and Steen (2000) emphasises the resource consumption impact over emissions such as CO₂. For HDPE, the contribution of resource consumption to the final EPS indicator value was 71%, while it was 77% for mild steel. This is one reason why HDPE scored better than mild steel only with the EPS indicator. EPS also assigns relatively low impact values to NO_x and PM₁₀ emissions. Three EPS impact categories (for the HDPE fuel tank) show impacts of NO_x and PM₁₀ emissions in the detailed software results. In one of these categories, biodiversity, the 79% reduction in NO_x emissions in this category resulted in a less than 2% change in the biodiversity category impact contribution to the overall EPS indicator value. Together with the ecosystem productive capacity and human health categories, the decrease in NO_x and PM₁₀ emissions resulted in changes of less than 0.31% in the overall EPS indicator value. In contrast, using the LIME Version 2 indicator (HDPE fuel tank), each of the NO_x and PM₁₀ impact indicator contributions decreased by a factor of at least three in response to the decrease in NO_x and PM₁₀ emissions, causing a decrease in the overall indicator of about 25%—a more significant shift compared to the less

than 0.31% shift with the EPS indicator. This considerable difference in emphasis between the LIME and EPS indicators may be due to at least some of the following factors. Local pollutants such as NO_x and PM₁₀ are a great concern in Japan: they are emitted by industrial facilities which are invariably close to residential areas, as well as by motor vehicles. Japan has a much higher population concentration than Sweden (337 people/km² vs 21 people/km²), while the most heavily populated parts of Japan, the Kanto, Kansai and Chubu regions located on the main island of Honshu, do not have strong winds to help disperse air pollution (Ushiyama 1999). Lastly, the populated areas of Japan are generally the windless basins and not high-lying ground.

When pollution control was applied, slag inventory changes had very little effect on indicator values, reflecting the non-toxicity of slag.

Inventory results from the previous papers are of course dependent on assumptions made for the calculations. With the exception of the Yamato and Mituhara (1997) paper, the other papers generally show higher inventory values for steel. Similarly, the results presented here also show steel to have higher inventory values for most of the inventory items. However, impact assessments using a comparable range of indicators are not carried out for the other studies, which have been reviewed earlier. This includes the work by Tung and Wang (2002), which while employing weighting factors, does not do so for widely used indicators, neither for a comparable range of indicators. The merit of the impact assessment results is evident here as it evaluates the seriousness of each of the burdens and emissions associated with each of the fuel tanks. Further, it compares the results from a range of six indicators with comparable objectives and methodologies.

6.1 Manufacturing material waste

Assumptions about material waste in the manufacturing phase have been made in the methodology. We have assumed 24%

material waste (overall scrap rate) for steel and 1.7% material waste for HDPE in accordance with Nippon Steel (2009) and Keoleian et al. (1998), respectively. However, according to another study (Alvarado 1996), “The moulding process for plastic fuel tanks...As is the case for other applications, this process results in roughly 30% of plastic material ending as industrial waste”. The 30% waste of materials for HDPE would significantly increase the environmental impact related to the manufacture of the HDPE fuel tank, so the 1.7% (Keoleian et al. 1998) value needs to be verified or contextualised.

6.2 Post-recycling of materials

The incineration and landfilling of HDPE, which are the current common practices globally, both create resource depletion problems for crude oil. Steel is commercially recycled, and more recycling could realize an improvement in the resource depletion situation for steel. It has not been possible to apply the assumption of mild steel post-recycling in the complete inventory and the impact assessment because of the mentioned limitations in the JEMAI data. If the subsequent uses of the mild steel were considered, the relative impact of the mild steel as used for a car fuel tank would be further reduced. In particular, iron reserves, coking coal, combustion coal and limestone inventory amounts would be reduced to about 1/6th (about 17%) of the values reported here, based on an estimated 62 years use time of steel for Japan (Matsuno et al. 2007), which includes 10 years during which the steel is part of the fuel tank. A significant commensurate reduction in the relative impact assessment contribution of these items would result.

6.3 Other factors

There are other differences between the use of the steel vs HDPE fuel tank which have not been considered, such as the need for dissimilar car underbelly cover for the protection of the fuel tanks, which for example might cause dissimilar additional weight burdens on the car. Another source of uncertainty is the amount of fuel that seeps through the HDPE fuel tank body (permeation) as noted by Alvarado (1996), as opposed to the impermeable steel tank, although this absorbed gasoline is insignificant when compared to the gasoline requirement in the use phase. On the other hand, steel is susceptible to corrosion while HDPE is not, a relevant factor when the tank is used for long time in a corrosive environment.

7 Conclusions

Based on the assumptions and data sources in this paper, HDPE and mild steel car fuel tanks in Japan currently have

similar overall environmental impacts. The material with the higher inventory between the two depends on the inventory item being considered, with mild steel showing a higher inventory for iron, manganese, zinc, coal, limestone, NO_x , PM_{10} , SO_2 and hydrocarbons and solid waste in the form of slag to landfill. HDPE has a higher inventory for LNG reserves, oil reserves, CO_2 and SO_2 . The impact assessment using six indicators, without considering pollution control equipment, shows HDPE and steel to have very similar impacts for all but one of the indicators.

When modelling the maximum pollution control scenario, the various indicator values for the two materials decreased by up to 29%. As suggested by an analysis of the inventory, an impact assessment factoring in the feasible reduction in local pollutants shows improved relative performance of mild steel compared to HDPE. It is necessary to conduct an LCA of the pollution-control equipment. Consideration of the subsequent uses of the mild steel (recycling) would further improve the impact assessment of the mild steel relative to HDPE. In particular, the coking coal, combustion coal and limestone inventory amounts would be reduced to about 1/6th (about 17%) of their original values with a significant commensurate reduction in the impact assessment contribution of these items.

Acknowledgements We wish to thank the National Research Foundation (NRF) of South Africa and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan for making this research possible.

References

- Aamink AJA, van Hattum T, Hol A, Zhao Y (2007) Reduction of fine dust emission by combi-scrubber of Big Dutchman. A study funded by the Dutch government ministries LNV and VROM. <http://www.asg.wur.nl/NR/rdonlyres/F81D8745-6596-4296-A292-8553950E2B98/48334/66E.pdf>, published August 2007, accessed July 2009
- Alvarado PJ (1996) Steel vs. plastics: the competition for light-vehicle fuel tanks. *JOM* 48(7):22–25
- Bellmann K, Khare A (1999) European response to issues in recycling car plastics. *Technovation* 19(12):721–734
- Bengtsson M, Steen B (2000) Weighting in LCA—approaches and applications. *Environ Prog* 19(2):101–109
- Brogren C, Karlsson HT (1998) Modeling the absorption of SO_2 in a spray scrubber using the penetration theory. *Chem Eng Sci* 52 (18):3085–3099
- Burtraw D, Palmer K, Bharvirkar R, Paul A (2001) Cost-effective reduction of NO_x emissions from electricity generation. *Resources for the Future*, Washington D.C., Discussion paper 00–55REV, July 2001
- CBPR (2009) Embodied energy coefficients—alphabetical. Centre for Building Performance Research University of Wellington, Victoria, New Zealand. <http://www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf>, accessed July 2009
- EDMC (2008) Handbook of energy and economic statistics in Japan. The Energy Data and Modelling Center, The Institute of Energy Economics, Japan

Ehsan Md, Al Nur M (2003) Controlling emissions from conventional road transports: Dhaka situation. Proceedings of the International Conference on Mechanical Engineering 2003 (ICME2003), 26–28 December 2003, Dhaka, Bangladesh

ELCD (2007) The European reference life cycle data system. European Commission. <http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm>, published 2007, accessed October 2008

Forzatti P (2001) Present status and perspectives in de-NOx SCR catalysis. *Appl Catal A*: Gen 222(1–2):221–236

Hayashi Y, Kato H, Teodoro RVL (2001) An analysis of the effects of car and fuel taxes on CO₂ emissions in Japan and Germany. In: *Transportation, Energy and Environmental Policy: managing transitions*. The Transportation Research Board, Washington DC

Hendrickson CT, Lave LB, Matthews HS (2006) Comparison of steel and plastic fuel tank systems for automobiles, chapter 7. In: *Environmental life cycle assessment of goods and services: an input–output approach*. RFF Press, Baltimore

Holt GA, Baker RV, Hughs SE (1999) Evaluation of static pressure drops and PM10 and TSP emissions for modified 1D-3D cyclones. ASAE Annual International Meeting. Paper by Holt GA, Baker RV, Hughs SE, published July 19, 1999

Hunkeler D, Yasui I, Yamamoto R et al (1998) LCA in Japan: policy and progress. *Int J Life Cycle Assess* 3(3):124–130

Itsubo N, Inaba A (2003) A new LCIA method: LIME has been completed. *Int J Life Cycle Assess* 8(5):305

JEMAI (2008) JEMAI LCA-Pro database and software. The Japan Environmental Management Association for Industry (JEMAI), Tokyo, Software version purchased September 2008

Joshi S (1999) Product environmental life-cycle assessment using input–output techniques. *J Ind Ecol* 3(2–3):95–120

Kaspar J, Fornasiero P, Hickey N (2003) Automotive catalytic converters: current status and some perspectives. *Catal Today* 77(4):419–449

Keoleian GA, Spatari S, Beal R (1997) Life cycle design of a fuel tank system. National Risk Management Laboratory, US Environmental Protection Agency. <http://www.p2pays.org/ref/07/06431.pdf>, accessed January 2009

Keoleian GA, Spatari S, Beal RT, Stephens RD, Williams RL (1998) Application of life cycle inventory analysis to fuel tank system design. *Int J Life Cycle Assess* 3(1):18–28

Keoleian GA, Blanchard S, Reppe P (2000) Life-cycle energy, costs, and strategies for improving a single-family house. *J Ind Ecol* 4 (2):135–156

Lave LB, Joshi S, Maclean HL, Horvath A, Hendrickson CT, McMichael FC (1998) Environmental input–output life cycle analysis: a summary of results including a comparison with SETAC approach. Total life cycle conference and exposition. The Engineering Society for Advancing Mobility Land Sea Air and Space International, Graz

Matsuno Y, Daigo I, Adachi Y (2007) Application of Markov chain model to calculate the average number of times of use of a material in society. An application methodology for open-loop recycling: part 2: case study for steel. *Int J Life Cycle Assess* 12 (1):34–39

MIT (2008) On the Road in 2035: reducing transportation's petroleum consumption and GHG emissions. Report by MIT Laboratory for Energy and the Environment. <http://web.mit.edu/sloan-auto-lab/research/before2/otr2035/>, Massachusetts Institute of Technology, Cambridge, Massachusetts

Motz H, Geisele J (2001) Products of steel slags an opportunity to save natural resources. *Waste Manage* 21(3):285–293

Mouzakis DE, Karger-Kocsis J (1998) Effects of gasoline absorption on the tensile impact response of HDPE/SelarTM laminar microlayer composites. *J Appl Poly Sci* 68(4):561–569

Nippon Steel (2009) Mainly fuel tank finishing data obtained through private communication with Nippon Steel Corporation of Japan, Kitakyushu Factory

Norgate TE, Rankin WJ (2002) The role of metals in sustainable development. CSIRO metals, Australia. http://www.minerals.csiro.au/sd/CSIRO_Paper_LCA_Sust.pdf, accessed October, 2008

Product Ecology Consultants (2009) The Eco-indicator 95, Final Report. Pre, Amersfoort, The Netherlands. <http://www.pre.nl/download/EI95FinalReport.pdf>, accessed July 2009

Product Ecology Consultants (2010) LCA data in SimaPro. Pre, Amersfoort, The Netherlands. http://www.pre.nl/simapro/inventory_databases.htm, accessed July 2010

Stephens RD, Williams RL, Keoleian GA, Spatari S, Beal R (1998) Comparative life cycle assessment of plastic and steel vehicle fuel tanks. Presented at total life cycle conference and exposition. The Engineering Society for Advancing Mobility Land Sea Air and Space International, Graz

Tufts (2008) Note on steel embodied energy. Tufts University, Massachusetts, USA. <http://www.tufts.edu/tie/SGH/recycledmaterials.htm>, accessed December 2008

Tung C-y, Wang MH (2002) Comparison of environmental performance between plastic and steel fuel tanks. *Proc IME B J Eng Manufact* 216(11):1443–1457

University of Massachusetts (2008) Note on differences in energy required to make virgin and recycled steels. http://www.umass.edu/recycle/recycling_benefits.shtml, accessed December 2008

Ushiyama I (1999) Wind energy activities in Japan. *Renew Energ* 16 (1–4):811–816

Yamato M, Mituhara Y (1997) Life Cycle Inventory Study of Automotive Fuel Tank. Report by Masako Yamato and Yoshihito Mituhara of Toyota Motor Corporation. www.sae.org (document number 971177), accessed October, 2008